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by

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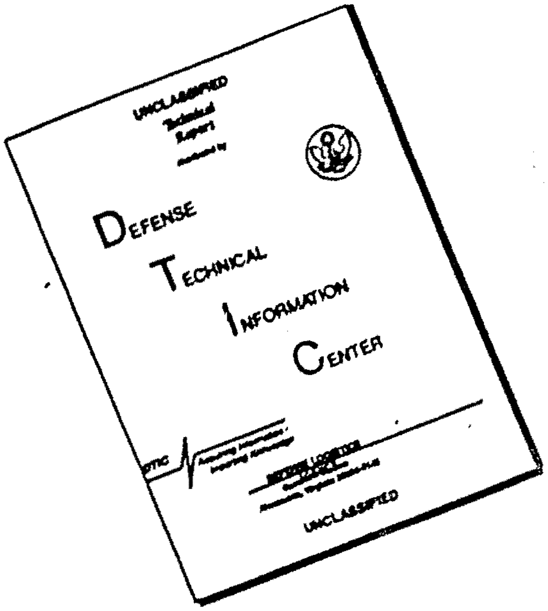

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EXPERIMENTAL DETERMINATION OF HELICOPTER TIP VORTEX GEOMETRY USING SMOKE

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INTRODUCTION

In order to improve rotor performance, reduce vibration at all speeds, and produce helicopters whose maximum speed is power limited rather than vibration limited, better methods of rotor harmonic airloads computation are needed. Recent work using digital computers to calculate rotor harmonic airloads by integration of the Biot Savart relation over the vortex wake has resulted in much better agreement with experimental airloads than classical uniform inflow theories (Refs. 1 and 2). This work has also shown that the tip vortex is the source of most of the higher harmonic airloads since it is the most concentrated vortex in the wake. To obtain further improvements in rotor airloads prediction a better knowledge of the tip vortex geometry than the classical skewed helix is necessary. To validate theoretical computations of the tip vortex geometry some good experimental data is needed. The object of this study is to provide such experimental data by emitting smoke from the tip of one blade of a two bladed rotor mounted in a wind tunnel so that the smoke is entrained by the tip vortex. The resulting smoke trace is photographed by a pair of cameras and a data reduction process is used to eliminate lens distortion and parallax.

1. EXPERIMENTAL APPARATUS AND TECHNIQUES

The apparatus was a two bladed, full articulated rotor powered by a DC electric motor and mounted in a low speed, closed return wind tunnel. Hot oil smoke, provided by an external generator, was emitted from the tip of one of the rotor blades. The resulting smoke trace was photographed by a pair of cameras using three synchronized strobes for lighting.

1.1 Wind Tunnel

A low speed wind tunnel capable of speeds up to 88 ft/sec was used. This was a closed return type having a 5' x 7.5' test section and a larger return section. Some preliminary work was done using a rotor mounted in the return section because this 10 x 14 section allowed the use of a larger rotor and gave better fields of view for the cameras. It was necessary later to move to the 5' x 7.5' test section, using a smaller rotor, because excessive turbulence in the return section resulted in random, unpredictable variations in the wake geometry.

1.2 Rotor

The rotor radius (R) was 22.67 inches measured from the center of rotation. The flapping hinge offset was 1.3 inches, the lagging hinge offset was 2.3 inches, and the root cutout was 6.5 inches. The blades had zero twist, a constant chord of 2.5 inches, and a constant NACA 0015 airfoil section. Each blade weighed 0.97 pounds, was balanced about the ¼ chord, and had a moment of inertia about the flapping hinge of 0.0184 slug-ft/sec^2. The corresponding Locke Number was 1.08.

The blades were constructed of white pine with a 1/8" x 1/2" copper tube buried along the 1/3 chord line. This tube carried the smoke from the root cutout to the tip cap. A 5/8 inch wide aluminum tip cap was used to turn the smoke 90° from the spanwise direction to the chordwise direction. The smoke was emitted downstream from a ¼" x ¼" hole cut back ½ inch into the trailing edge of the tip cap and located 5/16 inch in from the blade tip (see Fig. 1). An alternate configuration was tried where holes were drilled in the copper tube through the upper surface of the blade along the entire span of the blade and where, instead of a ¼ inch hole in the trailing edge, the tip cap had many small holes drilled in its upper and lower surfaces. This was intended to show the location of the inboard portion of the wake but the only clearly defined vorticity that could be observed was the tip vortex and this approach was abandoned.

A four bladed rotor hub was used although only two blades were mounted on it for the initial tests reported here. Both flapping and lead-lag freedom was provided with the flapping hinge inboard of the lead-lag hinge (see above). There was no swash plate and blade pitch could only be changed when the rotor was stopped.

The hub was mounted 40 inches from the wind tunnel floor on a hollow steel shaft. The shaft was in the middle of the tunnel and ran from a motor mounted below the tunnel floor to a bearing mounted above the tunnel ceiling. Smoke entered the hollow shaft through a rotating seal in the upper bearing assembly. The smoke was transferred from a fitting on the upper part of the hollow shaft to the inboard end of the copper tubing at the root cutout of the blade by a piece of flexible plastic tubing. Since the flapping and lead-lag hinges were inboard of the root cutout the plastic tubing flexed due to flapping and lead-lag motion providing some damping. To provide equal damping a dummy piece of plastic tube was therefore attached to the other blade as well although no smoke was transmitted through it.

1.3 Smoke Generator

The smoke generator was a low pressure container with an internal heating element which vaporized silicone base, high temperature oil (Mobilsol A) to produce dense, white, nontoxic smoke. To avoid combustion of the oil the generator was slightly (less than 1 psig) pressurized with nitrogen. The nitrogen was also used to force the smoke out of the generator, through a condensate collector to the rotating seal, down the shaft, through the plastic and copper tubing to the blade tip and finally out into the tip vortex. The amount of oil used, the heating element temperature, the time allowed for the oil to vaporize, and the nitrogen pressure were varied by trial and error to obtain a satisfactory smoke trail.

1.4 Cameras and Lighting

Two cameras were used to photograph the wake: a camera mounted on the floor of the wind tunnel just downstream of the rotor shaft and a camera outside the wind tunnel shooting through a plexiglass window in the side of the test section (see Fig. 2). Since the bottom camera was only 34 inches below the rotor hub and even closer to the wake a "fish eye" wide angle lens (Takumar 18 mm) was used to provide the necessary field of view.

Both cameras used Polaroid 4 x 5 inch film holders and Polaroid Type 57 3000 speed black and white film. This film develops in 10 seconds allowing rapid trial and error adjustment of the lighting and the smoke. When a satisfactory set of photographs was obtained, they were rephotographed using Polaroid positive-negative film. The resulting negatives were used to make enlargements on 8 x 10 inch high contrast enlarging paper to allow more accurate measurements of the smoke trail.

Three Honeywell strobanar strobe lights were used to illuminate the smoke trail. Two of the strobes were placed about $2\frac{1}{2}$ rotor radii downstream and a little above the rotor hub at the sides of the wind tunnel. The third strobe was placed on the wind tunnel floor a little ahead of the rotor. The location of the strobes and the direction of aim was varied to eliminate the strobes and their reflections from the photographs as much as possible while providing maximum illumination of the smoke. Those portions of the wind tunnel wall and ceiling photographed by the cameras were painted with a black paint containing large amounts of carbon black to minimize reflections and to provide a contrasting background for the smoke.

To provide simultaneous side and bottom photographs both camera shutters were held open manually for about a second and the picture was taken by firing the three strobes simultaneously. The strobes were connected electrically to function as a master and two slaves. The master strobe was fired by a microswitch mounted on the rotor shaft which was adjusted to provide photographs at the desired blade azimuthal position, typically with the smoke emitting blade pointed upstream.

1.5 Operating Procedure

The basic variables were wind speed (V, feet/sec), rotor angular velocity (Ω, radians/sec), rotor shaft angle (α, radians), and collective pitch (θ, radians). The rotor shaft angle α was very difficult to change since the upper bearing assembly had to be relocated and new holes cut in the wind tunnel floor and ceiling for the shaft. All runs were therefore made with the shaft tilted $8^\circ 30' \pm 5'$ from the perpendicular, into the wind ($\alpha = + .148$), see Fig. 2. At about 500 rpm the shaft started to vibrate excessively so all runs were made at 400 rpm ($\Omega = 42$ radians/sec). Higher

rpm could have been achieved by adding another bearing inside the wind tunnel but the wires needed to support the bearing would have disturbed the flow around the rotor. The desired advance ratios ($\mu = \frac{V}{\Omega R}$) were therefore obtained by varying wind tunnel speed (V) with Ω held constant. The desired thrust (C_T when nondimensionalized by $\rho \pi R^2 \Omega^2 R^2$) was obtained by varying the pitch (θ).

To make a set of runs the first step was to set the pitch (θ) of each blade. Due to play in the rotor hub mechanism the estimated error in setting θ was ± 30'. The next step was to run the rotor at 400 rpm in hover, and use a strobe to check the blade tracking. If necessary, the pitch of one of the blades was adjusted to improve tracking. Once the tracking in hover was satisfactory the smoke generator was warmed up, tested, and if necessary, adjusted to give a satisfactory smoke trail. Then, with the rotor running at 300-400 rpm, the wind was turned on and run up to the desired V as measured by a hot-wire. The rotor rpm was adjusted to 400 ± 10 using the strobe, the blade tracking was checked, and the wind speed was checked again. The nitrogen valve was opened to force the smoke out the blade tip and when a satisfactory trail was achieved the lights were shut off and a set of photographs was taken. The photographs were checked immediately and if they were not satisfactory the lighting and/or smoke was adjusted as necessary. When satisfactory photographs were obtained another photograph was taken using the side camera only and a flood light instead of the strobes to determine the tip path plane inclination relative to the free stream (i).

2. DATA REDUCTION

The data reduction involved removing two kinds of distortion from the photograph: the distortion due to the "fish eye" lens used on the bottom camera and the distortion because the cameras were not infinitely far away from the smoke trail (parallax). The desired result was a set of drawings of the smoke trail as seen by observers at infinity looking down perpendicular to the tip path plane and looking from the side parallel to the tip path plane.

The coordinates of the smoke trail in the side photographs were measured relative to a set of axes mounted on the wall of the wind tunnel opposite the side camera, see Fig. 2. This side coordinate system consisted of a pair of aluminum bars with one inch markings mounted parallel to the wind tunnel wall with one bar parallel to the wind and the other perpendicular to the wind.

The coordinates of the smoke trail in the bottom photographs were measured relative to a coordinate grid mounted on the ceiling of the wind tunnel, see Fig. 2. A complete grid of 2 inch squares was used for the bottom coordinate system instead of the simple bars used for the side coordinate system because of the "fish eye" lens distortion of the bottom camera. Since the coordinate grid was distorted by the lens in the same way as the smoke trail, the distortion of the smoke trail due to the lens was removed by measuring the coordinates of the smoke trail in the distorted bottom photograph relative to the grid appearing in the background and plotting the result on normal rectangular graph paper.

To eliminate parallax and determine the correct three dimensional coordinates of the smoke trail it was necessary to locate corresponding points on the side and bottom view photographs.

For easily identified points such as the rotor hub and the blade tip this was relatively easy. On the smoke trail, however, specific points could not be so easily identified. The solution was to construct the line of sight from the lens of either the side or the bottom camera to a point on the image of the smoke trail in the plane of the corresponding coordinate system. A set of similar lines of sight was then constructed from the lens of the other camera to a series of points on the image of the smoke trail in the plane of the corresponding coordinate system until one of these lines intersected the line from the first camera. This intersection was then the actual location of the point on the smoke trail corresponding to the points on the two images of the smoke trail, see Fig. 2.

Initially this process of constructing lines of sight, finding the intersections, and computing the three dimensional coordinates of the intersections was done using a digital computer. Since the discovery of an exact intersection of two lines of sight was very unlikely in a finite number of attempts the computer calculated the miss distance (distance of closest approach) for each pair of lines of sight it was asked to investigate and searched for local minimums in the miss distance. For each local minimum in the miss distance the three dimensional coordinates of the midpoint between the two lines of sight at their closest approach was computed and transformed into the desired tip path plane referenced coordinate system. It was anticipated that, once sufficiently small miss distances were achieved, an accurate set of coordinates would be obtained. Minimum miss distances of less than 0.1 inches (some as small as 0.001 inches) were obtained for pratically every desired point on the smoke trail, but the results were clearly not correct, containing kinks and even loops which did not appear in the photographs. Investigation proved that these results were extremely sensitive to errors in the input data. Since the precise location of the center of the smoke trail on the photographs was

often a matter of judgement this seemed to make the use of the computer impractical.

To provide a better understanding of the difficulties with the data reduction it was decided to construct a physical model of the data reduction process. The model consisted of a rectangular plexiglass box with two faces representing the side and bottom view coordinate systems and with holes in the two opposite faces representing the side and bottom view cameras. The lines of sight were represented by wires running from the holes representing the cameras to points on the faces representing the coordinate systems. Sighting devices were constructed to determine the three dimensional coordinates of the intersection of the wires using accurate grids scribed on the plexiglass faces. This model made it possible for the operators to investigate a range of possible locations of the center of the smoke trail and to choose the correct one. Unfortunately the use of this model required a considerable amount of judgement on the part of the operators and proved to be very time consumming.

The use of the model of the data reduction process provided some useful insight into the problem which resulted in improvements in the data reduction computer program and a better understanding of how to use the program. This improved computer program with the aid of the model to determine the best inputs for the program in the difficult areas where the side camera line of sight is almost parallel to the smoke trail provides an adequate solution to the data reduction problem.

3. RESULTS

Nine test runs were conducted using the two bladed rotor covering an advance ratio range of $\mu = 0.1$ to 0.3 and C_T/σ from about 0.05 to 0.10. A typical test result for $\mu = 0.1$ and $C_T/\sigma = 0.075$ is shown in Fig. 3. Preliminary analysis indicates that the distortion from the rigid wake assumption of a skewed helix is appreciable, although qualitatively the results agree with theoretical nonrigid wake analysis. Complete reduction of the data and comparison with theory is now underway in connection with an associated research program and results will be ready shortly.

In general, the experimental techniques developed in the course of this program have proven to be successful and invaluable as a means of providing correlation with the very difficult analytical treatment required to predict the actual tip vortex geometry, which is evidently highly distorted.

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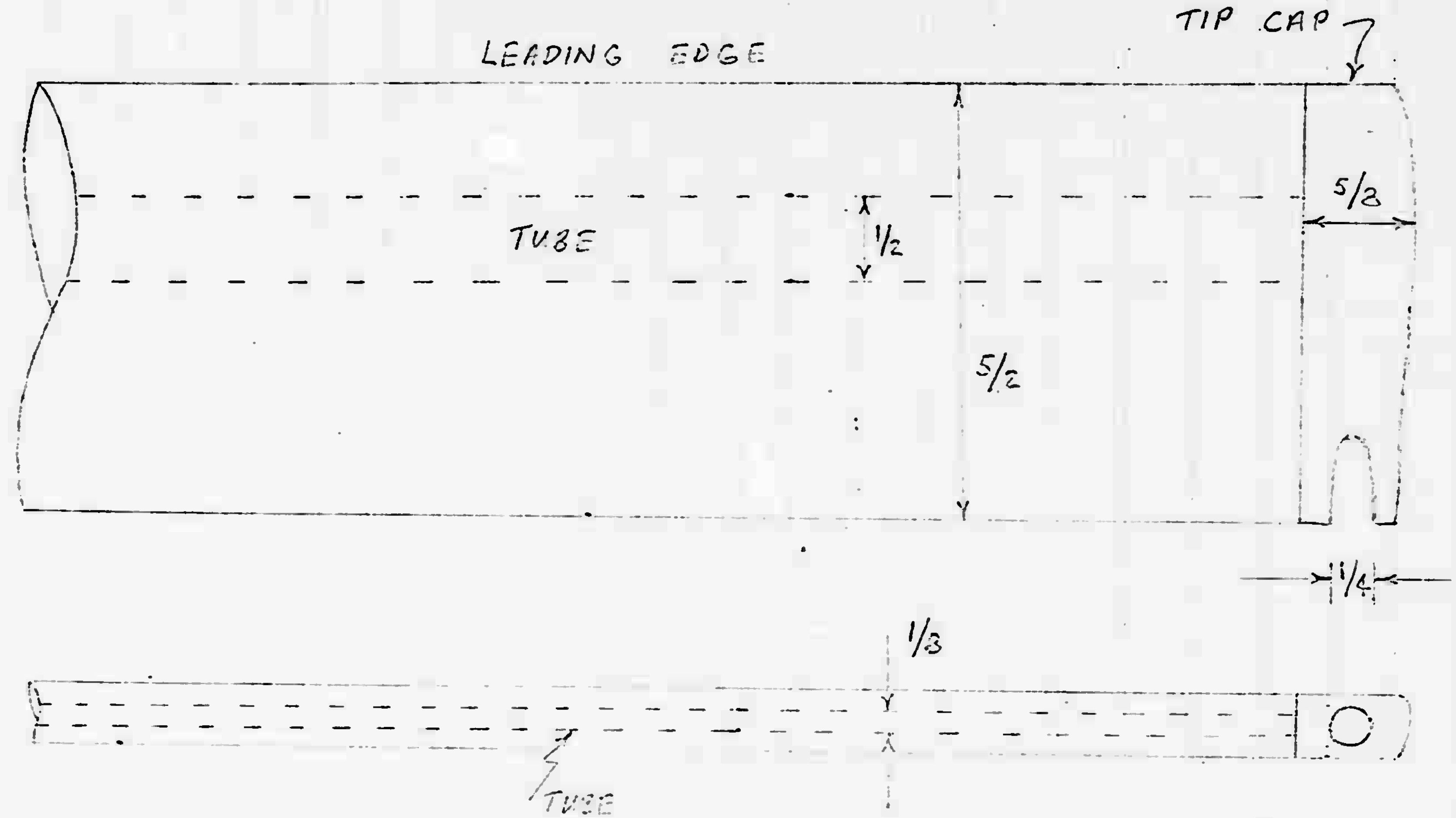

FIGURE 1 : ROTOR BLADE AND TIP CAP (INCH DIMENSIONS)

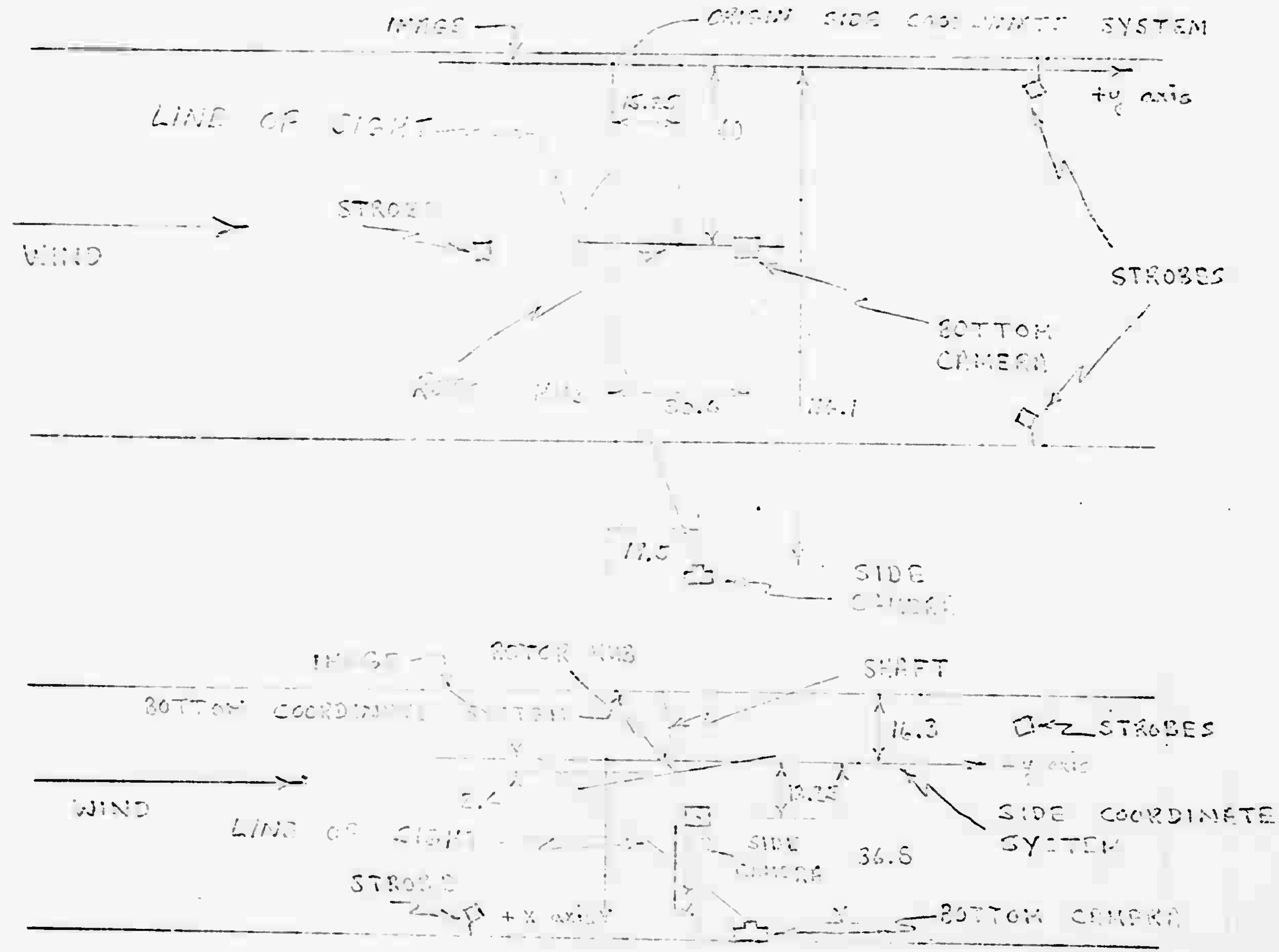

FIGURE 2 : TEST SETUP (INCH DIMENSIONS)

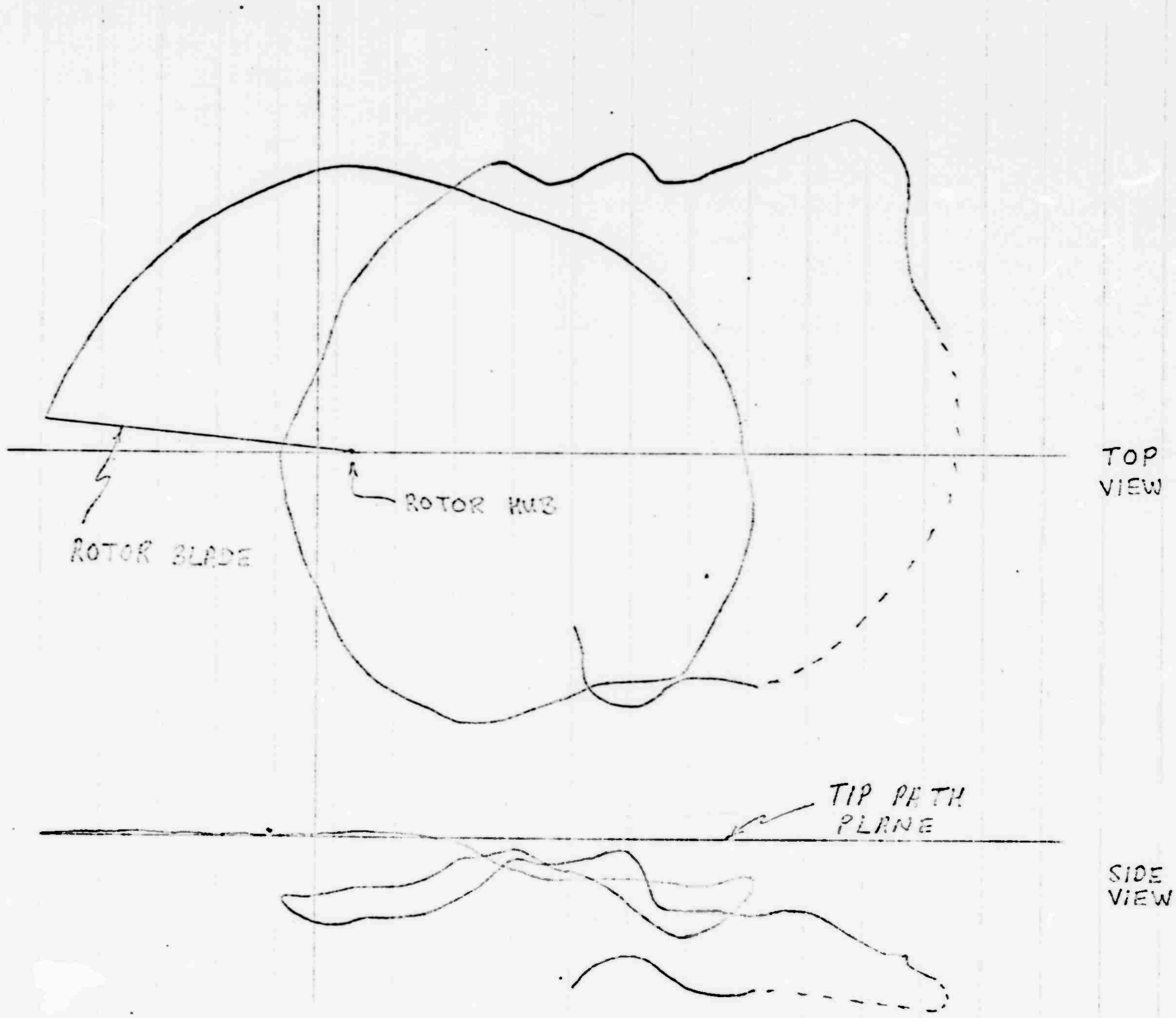

FIGURE 3 : REDUCED DATA FOR $\mu = .1$, $C_T/\sigma = .075$

——— TIP VORTEX - - - - - ESTIMATE, SMOKE TRAIL OBSCURED

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13. ABSTRACT

Experimental techniques have been developed and proven to be successful as a means of providing correlation with the analytical treatment required to predict the actual tip vortex geometry of a helicopter rotor. The data was obtained by emitting smoke from the tip of one blade of a two-bladed rotor mounted in a wind tunnel so that the smoke is entrained by the tip vortex. The resulting smoke trace is photographed by a pair of cameras and a data reduction process is used to eliminate lens distortion and parallax.

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